total cross sections are effectively the scattering cross sections and are directly applicable to the theory.

The errors given in the "data" column of Table I are the root mean square statistical errors of the total of all data, since there was good consistency between the various runs. The increased error in the "corrected" column includes an estimate of uncertainty in the scattering corrections and in the dimensions and densities of scatterers. The assignment of mean energies (except in the "tickle-threshold" case previously discussed) may be in error by an estimated +5 or −10 kev, the latter error being greater because of possible undetected target thickening.

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Angular Distribution of 2.5-Mev Neutrons Scattered by Deuterium†

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The angular distribution of the scattering by deuterium of 2.5-Mev neutrons was measured by analyzing the distribution in energy of the recoiling deuterons in an ionization chamber. In the center of mass system the differential cross section exhibits a maximum for backward scattering of the neutron. The value at the maximum is more than twice the value at angles near 90°. Neutron-proton scattering observed under similar conditions showed a departure of not more than 10 percent from isotropic scattering.

INTRODUCTION

It was pointed out in an earlier paper[1] that the distribution in angle of scattered fast neutrons could be measured by analyzing the distribution in energy of the recoiling nuclei in an ionization chamber filled with the gas the scattering by which one wishes to investigate. If monoenergetic neutrons are used, the distribution in energy of the recoiling particles in the laboratory system gives a direct measure of the angular distribution of the scattered neutrons in the center of mass system, provided that the dimensions of the chamber are large compared to the range of the most energetic recoiling nuclei.

In order to fulfill this condition very high pressures are required for investigations of the scattering properties of hydrogen or deuterium for fast neutrons. In spite of the application of high collecting fields, difficulties were caused in the earlier work by the slow collection of the ions in the gas at high pressure, resulting in a lack of energy resolution. The lack of resolution was caused partly by the fact that the amplification was not entirely frequency independent for the very slow pulses, partly by the relatively small signal to noise ratio for a slow amplifier, and also by the possible superposition of pulses due to recoils and due to gamma-rays. The earlier work[1] did not give any evidence for an anisotropy in the scattering of 2.5-Mev neutrons by hydrogen or deuterium. It was pointed out in the earlier paper that, because of the lack of resolving power both in energy and angle, deviations from isotropy could have been detected only if they were large and varied slowly with angle. The distribution in energy of the recoiling deuterons showed the unexplained feature that its break at high energy occurred at an energy about 10 percent higher than should have been expected from a comparison with Po alpha-particles. This fact, in addition

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[1] H. H. Barschall and M. H. Kanner, Phys. Rev. 58, 590 (1940).

to an observed small rise of the energy distribution at the high energy end, and observations by Staub[2] of a considerably larger rise at the high energy end of the distribution curve for deuterons, indicated the desirability of repeating the experiments using a method which would yield better resolving power.

It is possible to use considerably lower stopping power if all the recoiling particles originate from a foil. In this case it is also feasible to employ the fast collection of electrons in a pure gas instead of the slow collection of positive ions. Under these conditions it was expected that a very much better resolution in energy and angle could be attained.

EXPERIMENTAL

Figure 1 shows the parallel plate ionization chamber[3] in which a thin radiator of about 50 μg cm^{-2} of evaporated normal or heavy paraffin was located on the high voltage electrode (3300 volts negative for the case of protons and 1900 for deuterons). Neutrons incident normal to the radiator ejected protons or deuterons into the chamber at all angles between 0° and 90°. The chamber was filled with krypton to a pressure such that forward recoils had a range of about 8 or 10 mm in the chamber; this pressure was 9.0 and 4.8 atmospheres, respectively, for protons and deuterons.

A third electrode consisting of a plane grid of fine wire (0.003″ Cu wires spaced at 1.5 mm) was located between and parallel to the two parallel plates and 1.3 cm from the high voltage electrode. The voltage applied to the grid was several hundred volts more negative than the potential which the plane of the grid would have assumed in the absence of the grid. Ionization electrons formed in the region between the grid and high voltage electrode are swept through the grid to the collector plate, thereby inducing a voltage pulse, the magnitude of which is entirely determined by the total charge carried by the electrons and by the distributed capacity of the collecting electrode system. The pulse reaches its full value in the relatively short time determined by the mobility of the electrons. Thus one obtains a fast pulse of magnitude proportional to the number of ion pairs formed, and therefore also to the energy of the ionizing particle. Since the pulse is fast, one can use an amplifier with a relatively narrow-band frequency response at high frequency. Use of such an amplifier has the advantage of reducing circuit noise level, eliminating microphonic troubles, and greatly decreasing the chance of superposition of small pulses due to gamma-rays or recoil gas atoms. In the absence of a grid the space in which the ions are formed is not electrostatically shielded from the collector, and the voltage pulse is the sum of

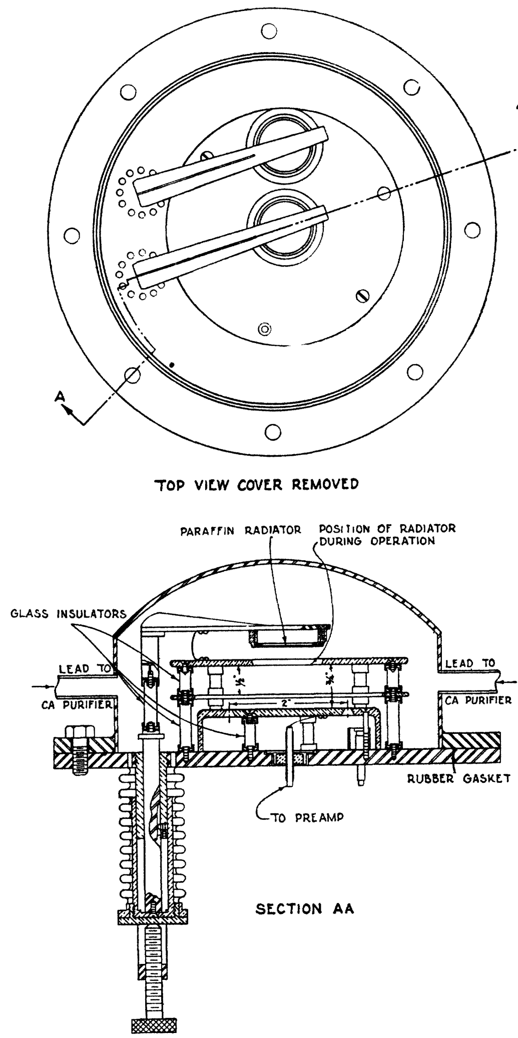

FIG. 1. Parallel plate ionization chamber with thin paraffin radiator.

[2] H. H. Staub, private communication.

[3] This chamber was borrowed from H. H. Staub and D. B. Nicodemus at this laboratory.

contributions by the electrons and by the positive ions.

To minimize trouble due to electron attachment and ion recombination in the gas, the krypton was continually purified by flowing over hot calcium metal at about 350°C.[4]

The pulses were amplified by a linear pulse amplifier[5] with rise time of about 0.5 μsec. and time constant 60 μsec. The observed time required for the collection of the electrons was several microseconds. The pulses were recorded by photographing an oscilloscope screen on 35-mm film and relative pulse heights were measured visually by use of a microfilm reader. An electronic pulse generator was used to impress voltage pulses on the grid of the first amplifier tube for the purpose of testing the constancy and linearity of the amplifying and recording equipment as well as for a standard in comparing pulse heights due to alpha-particles, recoiling protons, and recoiling deuterons.

The monoenergetic neutrons used were from the $d-d$ reaction and were produced in a thick heavy ice target by an analyzed beam of 200-kev atomic deuterium ions accelerated by a Cockcroft-Walton voltage quadrupler. The 1″ diameter radiator in the ionization chamber was located 5″ from the target and at 90° to the deuteron beam. The neutrons incident normal to the radiator had an energy of 2.53 Mev. The energy spread of the neutrons due to the angular range of 12° subtended by the radiator at the target was 110 kev. An additional neutron energy spread of about 30 kev results from the thick heavy ice target. The number of neutrons from the $d-d$ source was monitored by counting protons from the companion reaction $D(d, p)H^3$.

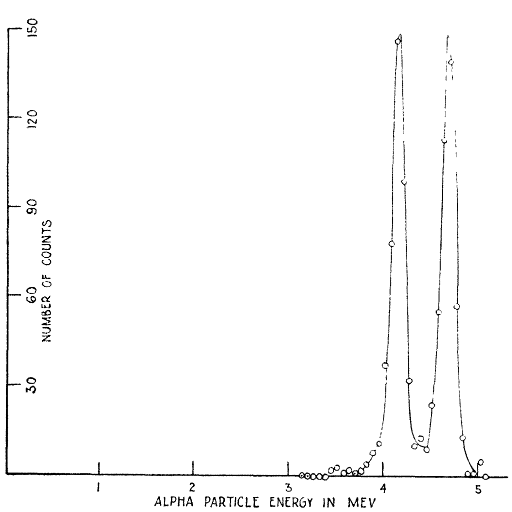

FIG. 2. Distribution in size of pulses due to alpha-particles from a normal uranium foil placed in the ionization chamber.

The paraffin radiator thickness was such that the maximum energy loss of a useful recoil (at maximum angle usable) was about 40 kev for protons and 70 kev for deuterons. Correction was made for the effect of radiator thickness on the energy distribution of the recoiling particles emerging from the radiator. The ratio of the number of deuterium atoms to the number of hydrogen atoms in the heavy paraffin was 62 according to the manufacturer.

For measuring background the Pt foil onto which the radiator was deposited could be replaced by an identical blank Pt foil by means of mechanical controls leading into the ionization chamber through sylphons. The background was minimized by lining the chamber parts with carefully cleaned platinum sheets. The counting rate was about 15 per minute of which 25 percent was background. The pulse height distribution of the background indicated that it was caused mainly by recoiling protons. Data were taken in cycles, the radiator and the blank foil being used alternately.

The best over-all test of the equipment was the counting of alpha-particles from a thin deposit of normal uranium placed in the position normally occupied by the paraffin radiator. Figure 2 shows the pulse height distribution obtained for the two alpha-particle groups. The width of the peaks at half maximum is about 150 kev. This energy resolution indicates that pulse height is independent of direction of the path of the ionizing particle though it is recognized that the relatively short range of the alpha-particle might affect the validity of this test. Comparison of the relative pulse heights due to uranium alpha-particles, and of proton and deuteron recoils of maximum energy gave pulse height values in the same ratio as the energy values with a maximum

[4] E. D. Klema and H. H. Barschall, Phys. Rev. **63**, 18 (1943).

[5] The circuits for this experiment were designed mainly by Matthew Sands and W. A. Higinbotham in this laboratory and were built by the electronics group here.

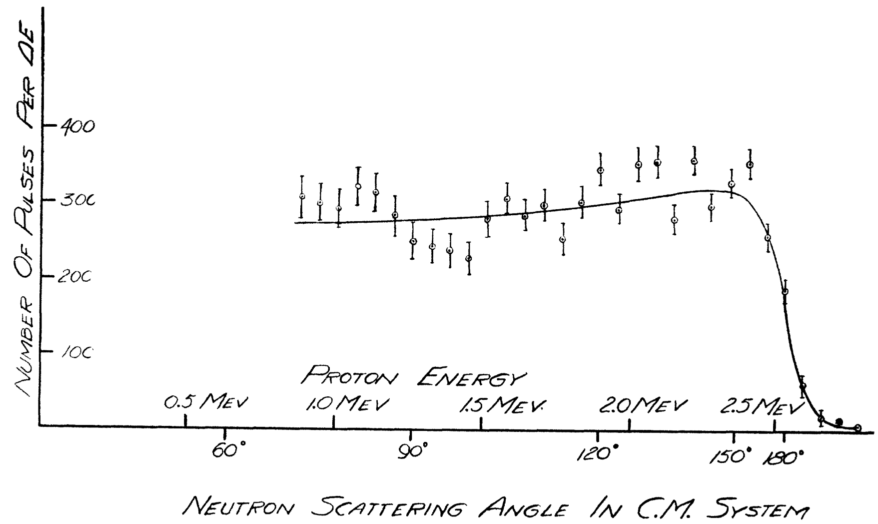

FIG. 3. Distribution in energy and in angle of protons recoiling from 2.53-Mev neutrons. The vertical lines represent standard deviations computed by taking the square root of the sum of the number of counts and the background counts.

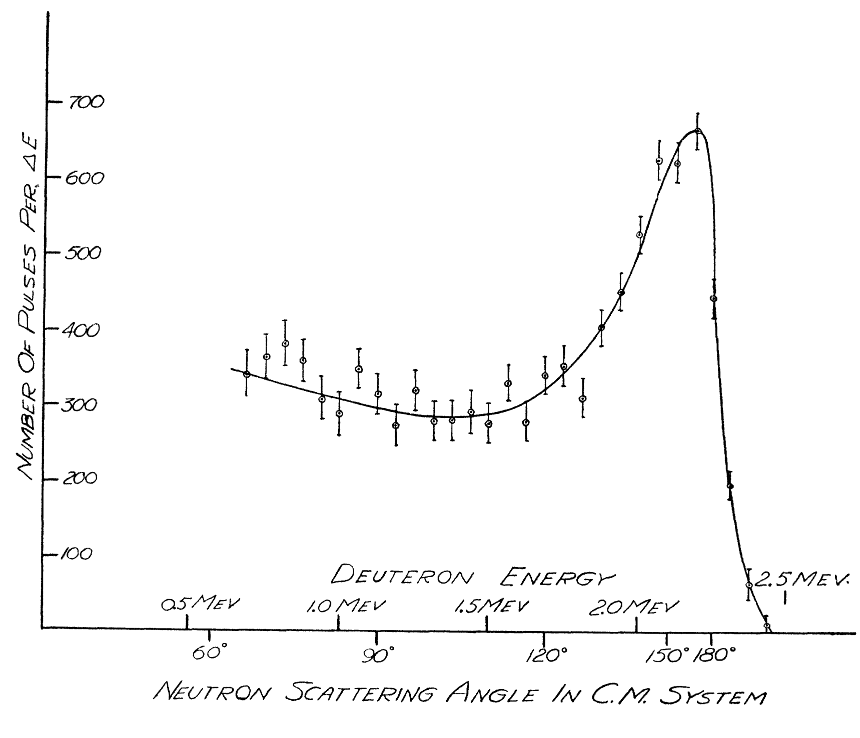

FIG. 4. Distribution in energy and in angle of deuterons recoiling from 2.53-Mev neutrons. The vertical lines represent standard deviations.

difference of 50 kev, which is as good agreement as can be expected from the accuracy of the measurements.

The effectiveness of the grid was tested by using a collimated source of alpha-particles. By changing the distance between source and grid it was determined that if the alpha-particle tracks terminated 2 mm from the grid less than one percent of the pulse height was lost.

Voltage saturation tests showed about a four percent drop in pulse height if the voltage was reduced to half the value used in each case.

RESULTS

Figures 3 and 4 show the pulse height distributions for recoil protons and recoil deuterons, respectively. The abscissae are normalized by taking the neutron energy as 2.53 Mev which is also the value of the maximum recoiling proton energy, while $8/9\times 2.53$ Mev is the maximum deuteron recoil energy. The neutron scattering angle in the center of mass system is indicated on a non-linear scale. The ordinates are the number of measured pulses (with background subtracted) in a small energy interval ΔE equal to the interval between successive points. The energy interval ΔE is constant over the whole energy range so that the ordinates represent directly the distribution in energy of the recoiling particles. Each curve represents about 12,000 counts. The minimum energy to which the data extend is determined by the maximum energy of carbon recoils or by the maximum energy loss by electrons ejected into the chamber by gamma-rays.

The energy width of the alpha-particle peaks at half-maximum is about 150 kev. The resolution is approximately the same in the case of the recoil measurements, though the rate at which the recoil distributions fall off at the high energy end indicates somewhat better resolution.

The curves in Figs. 3 and 4 are corrected for the effect of radiator thickness[6] on the energy distribution of recoiling particles emerging from the surface of the radiator. The maximum correction in the number of particles per energy interval ΔE is at the low energy end of the curves and amounts to 2 percent for protons and 8 percent for deuterons.

The gradual rise at higher energies shown in the case of protons is hardly outside the experimental uncertainty and is therefore not considered to be in disagreement with the theoretically expected isotropic scattering, which is supported by measurements at higher neutron energies.[7]

The sharp rise at high energy in the case of deuterons implies a preferential backscattering of neutrons by deuterons, with a differential scattering cross section at 180° more than twice that at 110°. Comparison of the area of the high energy hump of the curve with the total area (extrapolating to zero with a horizontal line) shows that about 15 percent of the scattered neutrons are contained in this backscattered maximum.

The cloud-chamber data of Kruger *et al.*[8] for $n-d$ scattering with 2.6-Mev neutrons agrees with the present results in giving a maximum for backscattering of the neutron, though their statistical accuracy is low because the total number of recoils they observed was only 328. According to data of Sherr,[9] the angular distribution of $p-d$ scattering with 2.5-Mev protons exhibits a backscattered maximum similar to, though somewhat larger than, the present measurements on $n-d$ scattering. The Coulomb contribution for $p-d$ scattering at the larger angles involved in backscattering can be neglected.

We wish to thank Mr. R. W. Davis for his help in taking the data and reading the records, and Mr. D. Rhoads for measuring some of the films.

[6] Calculations made by J. L. Magee.

[7] F. C. Champion and C. F. Powell, Proc. Roy. Soc. **A183**, 64 (1944). H. Tatel, Phys. Rev. **61**, 450 (1942).

[8] P. G. Kruger, W. E. Shoupp, R. E. Watson, and F. W. Stallmann, Phys. Rev. **53**, 1014 (1938).

[9] R. Sherr, C. Bailey, M. Blair, and H. Kratz, private communication.